Using history dependence to design a dynamic tradeable quota system under market imperfections

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Abstract

A transferable quota system is analysed in a two-period model with market power. So far, the management mechanisms presented in the literature to remedy market power have either not succeeded in securing efficiency in the distribution of quota *within* and *across time periods*, or have resulted in only one of the two inefficiencies being eliminated. In this paper a new mechanism is introduced where allocation of quota is made dependent upon historic quota acquisitions. This opens for a trade-off between distributional and time efficiency, or under specific circumstances securing overall efficiency.

Key words:

Transferable quota, market imperfection, history dependence

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Introduction

Tradeable quota regimes have received substantial attention as a possible solution to externalities due to pollution (Dales, 1968, Tietenberg, 1980, 1992). Transferable quotas have also been seen to be a potential remedy within renewable resource management, and are actively applied in a number of countries (Arnason, 1993, Hannesson, 1991, Hersoug, 2002). The economic rationale for transferable quotas is that the agents, in for instance a fishery, will be motivated to produce as efficiently as possible, due to the incentives underlying, and trades will take place ensuring that the most efficient operators utilise the quotas. Initial allocations of quota have traditionally been based on historic catch in the case of fisheries, and historic levels of emissions in the case of pollution. Hence, history dependence is a fundament upon which much management is built. That is, when implementing some form of property rights management to eliminate an externality, rights allocations are made based on some measurement of historic activity. This has also been the case in the implementation of individual transferable quotas (ITQs) in fisheries, where the managers, rather than sell the quota to the users, have allocated it for free (or almost for free), based on historic catch and sometimes capital input. Hence sharing out rights based on historic behaviour is seen as a legitimate mode of allocation. Furthermore, a development that has become increasingly visible in fisheries managed with ITQs, is the concentration of quota in the hands of a few harvesters (Anon, 2002, Anderson, 1991, Eithórsson, 2000, Armstrong and Sumaila, 2001)[1]. Hence it is of interest to study quota markets where the potential for market power is present and historic catch is the basis for allocation.

[1] Only one paper that explicitly tests for monopoly power in ITQ fisheries has been found. Adelaja et.al. (1998) test for market power in the output market of the Mid-Atlantic Surf Clam and Ocean Quahog fishery, and find it absent. The authors admit that the issue of large firms being vertically integrated and hence offering lower ex-vessel prices to own vessels was not taken into account. They also find that increased expansion of control of quota shares may compromise the existing competitive climate in the fishery.

Market power in quota markets has been extensively studied within the environmental economics literature, but the issue of history dependence has not received any attention in this context[2]. Hahn (1984) illustrated how market power in a static tradeable quota system gives potential for efficiency losses if the allocations are other than what the agents would hold in equilibrium. Van Egteren and Weber (1996) and Chavez and Stranlund (2003) show in static models how enforcement may mitigate Hahn's results. Cronshaw and Kruse (1996) describe a discrete time model with the possibility of banking quota. Rubin and Kling (1993) and Rubin (1996) study banking and borrowing in models of tradeable pollution permits. Hagem and Westskog (1998) design what they call a dynamic durable quota system and contrast it to the banking and borrowing (B&B) model. They show how the B&B model is conditionally time efficient; i.e. it can secure optimal behaviour *across* but not *within* time periods. Hence, market efficiency involving the elimination of market power is not ensured in the B&B model, while time efficiency is. In the durable model *perfect* market efficiency is not reached either, as the monopolist still sells less than the for the market optimal amount, but nonetheless more than in the B&B model. This due to the fact that in the durable model the buyer's expectations of a lower price in the second period reduces their demand in the first period. The durable model does not, however, secure time efficiency.

This paper illustrates how a model that gives the buyer an allocation in the second period that is some function of the quota bought in the first period, will under certain conditions secure market and time efficiency. It is of interest to study under what conditions this model outperforms the models previously applied, as regards efficiency. It is shown that a history dependent quota allocation model has potential to outperform a durable allocation model and at least match a leasing quota model, in that it can ensure either market or time efficiency.

[2] Bergland, Clark and Pedersen (2001, 2002, 2003) study history dependence in the implementation of a quota regime without studying the issue of transferability and concentration.

Under specific conditions the trade-off between market and time efficiency can also be eliminated.

In the next section a resource management model in the vein of Hagem and Westskog's (1998) pollution models, is designed, and the efficiency requirements analysed. The original model is expanded upon, allowing history dependent allocation, the results of which are compared to the models found in the literature. The paper concludes with a discussion of allocation modes found in actual fisheries management around the world.

The model

In the following three versions of a model of a quota market with market power is presented, namely, a durable, a leasing and a history dependent model. We assume two agents; a monopolist and competitive fringe; $i= M, F$, respectively, who operate in a natural resource market. The study is limited to two time periods; $j=1,2$.

Definitions:

Q_j is the total quota harvested in time period j, j=1,2, or the total allowable harvest determined by some regulator. We will assume that Q_j is determined exogenously, but can vary over the time periods.

z_j denotes the transferred harvest share between the two agents M and F in time period j.

$\overline{q}_{Fj}$ and $\overline{q}_{Mj}$ are the quota shares allotted each group (monopolist and fringe) in each time period, where $\overline{q}_{Fj} + \overline{q}_{Mj} = 1$ [3].

[3] It is assumed that the initial allocation is restricted by for instance equity considerations such that the quota shares allocated are not the shares held in equilibrium. Trading is therefore observed, as discussed in Hahn (1984).

q_{ij} is the harvested share, that is, the sum of the allotted share $\overline{q}_{ij}$, i=F, M, and the transferred share z_j in time period j.

p_{ij} is the unit market price of the harvest of group i in time period j.

$c_i(q_{ij})$ is the harvest cost of group i in period j, which depends on the share of harvest obtained, since the total quota Q_j is given.

τ_j is the price of a quota share in time period j

δ is the discount rate.

The profits of the fringe group and the monopolist in time period j is respectively described by:

$$\pi_{Fj}(q_{Fj}) = p_{Fj}Q_j q_{Fj} - c_{Fj}(q_{Fj}) - \tau_j z_j$$

and

$$\pi_{Mj}(q_{Mj}) = p_{Mj}Q_j q_{Mj} - c_{Mj}(q_{Mj}) + \tau_j z_j$$

where we will define

$$f_{ij}(q_{ij}) = p_{ij}Q_j q_{ij} - c_{ij}(q_{ij})$$

The following assumptions are made:

a) No unused quota (see (1) and (2) below)

b) No strategic action is made by either group to influence the total allowable harvest.

c) There is perfect foresight about future quota prices.

<u>We study three possibilities:</u>

I) Durable quotas; i.e. what is allocated and bought in period 1 can also be used in period 2, hence long term quotas.

II) Leasing of quotas; i.e. what is bought in period 1 can only be used in this period, hence short term quotas[4].

III) History dependence; i.e. what is allocated in the second time period is a function of the quota bought and sold in the first time period.

Let us first study the long-term model.

I) *Durable quotas:*

The harvested shares for the competitive fringe and the monopolist in the two time periods are:

(1) $q_{F1} = \bar{q}_{F1} + z_1$ and $q_{M1} = \bar{q}_{M1} - z_1$

(2) $q_{F2} = \bar{q}_{F1} + z_1 + z_2$ and $q_{M2} = \bar{q}_{M1} - (z_1 + z_2)$

See from (1) and (2) that [5]

(3) $\dfrac{\partial f_{Fj}}{\partial q_{Fj}} = \dfrac{\partial f_{Fj}}{\partial z_j}$ and $\dfrac{\partial f_{Mj}}{\partial q_{Mj}} = -\dfrac{\partial f_{Mj}}{\partial z_j}$

The object of the agents involved is to:

$$\underset{<q_{F1},\, q_{F2},\, z_1+z_2>}{\text{Max}}\ \Psi_F = f_{F1}(q_{F1}) - \tau_1 z_1 + \delta\{f_{F2}(q_{F2}) - \tau_2 z_2\}$$

and

$$\text{Max}\ \Psi_M = f_{M1}(q_{M1}) + \tau_1 z_1 + \delta\{f_{M2}(q_{M2}) + \tau_2 z_2\},$$

[4] Leasing quotas are studied instead of a banking and borrowing mechanism, as the latter is often deemed problematic in natural resource management.
[5] This presentation follows Hagem and Westskog (1998).

$<q_{M1}, q_{M2}, z_1+z_2>$

both s.t. their respective parts of (1) and (2). Efficiency requires:

(4) $\frac{\partial f_{Fj}}{\partial q_{Fj}} = \frac{\partial f_{Mj}}{\partial q_{Mj}}$, j=1,2, and $\frac{\partial f_{i1}}{\partial q_{i1}} = \delta \frac{\partial f_{i2}}{\partial q_{i2}}$, i=F, M

That is, the first equation ensures equal marginal productivity of quota share for each group, while the second equation demands equal (discounted) marginal productivity of quota share over time.

Let us start by studying the *fringe*;

Intuitively, since the quotas are durable, we have that the price the fringe is willing to pay in period 1 is

$$\tau_1 = \frac{\partial f_{F1}(q_{F1}(z_1))}{\partial q_{F1}} + \delta\tau_2,$$

hence $\tau_1 = \tau_1(z_1, \tau_2)$, and

(5) $\frac{\partial f_{F1}}{\partial q_{F1}} = \tau_1 - \delta\tau_2$

Also we intuitively have that

(6) $\tau_2 = \frac{\partial f_{F2}(q_{F2}(z_1 + z_2))}{\partial q_{F2}}$

Thereby making (again abusing notation)

$$\tau_2 = \tau_2(z_1 + z_2)$$

Let us now look at the monopolist in period 2:

Max $\{f_{M2}(q_{M2}(z_1 + z_2)) + \tau_2(z_1 + z_2)\cdot z_2\}$
$<z_2>$

Which using (3) gives FOC:

(7) $\dfrac{\partial f_{M2}}{\partial q_{M2}} = \tau_2(z_1 + z_2) + \dfrac{\partial \tau_2}{\partial z_2} z_2$

$\Rightarrow z_2 = z_2(z_1)$

Let us now study the monopolist in period 1. From the above we have that $\tau_1 = \tau_1(z_1)$ and $\tau_2 = \tau_2(z_1 + z_2)$, making the monopolist's problem:

Max $\Psi_M = f_{M1}(q_{M1}(z_1)) + \tau_1(z_1)\cdot z_1 + \delta\left[f_{M2}(q_{M2}(z_1 + z_2(z_1))) + \tau_2(z_1 + z_2)\cdot z_2(z_1)\right]$
<z$_1$>

This gives FOC (by applying (3)):

$$\frac{\partial f_{M1}}{\partial q_{M1}} = \tau_1(z_1) + \frac{\partial \tau_1}{\partial z_1} z_1 + \delta\left\{\frac{\partial f_{M2}}{\partial q_{M2}}\left[\frac{\partial q_{M2}}{\partial z_1} + \frac{\partial q_{M2}}{\partial z_2}\frac{\partial z_2}{\partial z_1}\right] + \tau_2\frac{\partial z_2}{\partial z_1} + \frac{\partial \tau_2}{\partial z_1} z_2\right\}$$

and since $\dfrac{\partial q_{M2}}{\partial z_1} = \dfrac{\partial q_{M2}}{\partial z_2} = -1$, and $\dfrac{\partial \tau_2(z_1 + z_2(z_1))}{\partial z_1} = \dfrac{\partial \tau_2}{\partial z_2}\dfrac{\partial z_2}{\partial z_1} + \dfrac{\partial \tau_2}{\partial z_1}$, applying (7) makes the FOC become

(8) $\dfrac{\partial f_{M1}}{\partial q_{M1}} = \tau_1(z_1) + \dfrac{\partial \tau_1}{\partial z_1} z_1 - \delta\tau_2$

Thus from (5) and (8) we see that the efficiency requirement of equal marginal productivity within time periods in the first equation of (4) does not hold. Furthermore, (7) and (8) do not satisfy the equal (discounted) marginal productivity of quota share over time in the second equation of (4). Hence we have neither efficiency between the groups, or over time. Hagem and Westskog (op.cit.) give some intuition about how this system nonetheless reduces market power's adverse effects due to the fact that in the durable good situation it is profitable for the monopolist to lower price in subsequent time periods in order to sell additional quota. The buyers' rational expectation of this may hurt the monopolist since the buyer will be willing to pay less for quota today in the anticipation of the future, hence reducing the monopolist's market power.

Let us now look at the short term model:

II) *Leasing of quotas*

The harvested shares for the competitive fringe and the monopolist in the two time periods are now described by:

(1) in the durable model is unchanged, while (2) is now;

(2*) $q_{F2} = \overline{q}_{F2} + z_2$ and $q_{M2} = \overline{q}_{M2} - z_2$

We see from (1) and (2*) that (3) still holds. The study of the fringe is changed as follows. Intuitively, since the quotas are no longer durable, we have that

(5*) $\dfrac{\partial f_{F1}(q_{F1}(z_1))}{\partial q_{F1}} = \tau_1,$

hence $\tau_1 = \tau_1(z_1)$.

Also we have that

(6*) $\tau_2 = \dfrac{\partial f_{F2}(q_{F2}(z_2))}{\partial q_{F2}}$

Thereby making (again abusing notation)

$\tau_2 = \tau_2(z_2)$

Thus the monopolist's problem in each period becomes:

Max $\left\{ f_{Mj}(q_{Mj}(z_j)) + \tau_j(z_j) \cdot z_j \right\}$
$<z_j>$

Which using (3) gives FOC:

(7*) $\dfrac{\partial f_{Mj}}{\partial q_{Mj}} = \tau_j(z_j) + \dfrac{\partial \tau_j}{\partial z_j} z_j$

Thus when comparing (5*) and (6*) with (7*), we see that the efficiency requirements of equal marginal productivity in (4) do not hold, unless $\frac{\partial \tau_j}{\partial z_j} z_j = 0$. Furthermore, (7*) does not satisfy equal (discounted) marginal productivity of quota share for the two groups, except under special conditions of equality, such as $\tau_1 = \delta \tau_2$ and $\frac{\partial \tau_1}{\partial z_1} z_1 = \frac{\partial \tau_2}{\partial z_2} z_2$[6]. Hence under special conditions we have efficiency between the groups, and/or over time.

Finally, let us include history dependence in the quota allocation scheme.

III) *History dependence*

In the following we study quota allocation depending upon previous quota use. The intuition behind the history dependent model is as follows: Each firm is allocated a certain amount of quota in each time period. This quota can be sold or used in order to harvest fish. In time period 1 the fringe and the monopolist get an allocation from the fisheries managers. The monopolist sells some of its' quota to the fringe. In period 2 the monopolists' new allocation is reduced by some function of the sold quota, while the fringe's allocation is increased in the same fashion.

We assume that:

$$\bar{q}_{M2} = \bar{q}_{M1} - g(z_1)$$
$$\bar{q}_{F2} = \bar{q}_{F1} + g(z_1)$$

The quotas in the second period become:

[6] It is probably not amiss to assume $\frac{\partial \tau_1}{\partial z_1} = \frac{\partial \tau_2}{\partial z_2}$, hence leaving the assumption that $z_1 = z_2$.

(2**) $$\begin{aligned} q_{M2} &= \overline{q}_{M1} - g(z_1) - z_2 \\ q_{F2} &= \overline{q}_{F1} + g(z_1) + z_2 \end{aligned}$$

If for instance $g(z_1) = bz_1$, then note that b=0 gives us the leasing model, and b=1 gives the durable model, as long as allocations stay unchanged over time. Other values of b result in some form of history dependent model. In essence the durable model is a perfect history dependent model – you get to keep everything that you bought in the previous period, while the leasing model is perfectly history independent – you get to keep nothing of what you bought in the last period.

The quota used in the history dependent model is determined by (1) in the first period and (2**) in the second period. Note that (3) still holds.

The object is to

$$\underset{<q_{F1},\, q_{F2},\, g(z_1)+z_2>}{\text{Max}} \ \Psi_F = f_{F1}(q_{F1}) - \tau_1 z_1 + \delta\{f_{F2}(q_{F2}) - \tau_2 z_2\}$$

and

$$\underset{<q_{M1},\, q_{M2},\, g(z_1)+z_2>}{\text{Max}} \ \Psi_M = f_{M1}(q_{M1}) + \tau_1 z_1 + \delta\{f_{M2}(q_{M2}) + \tau_2 z_2\},$$

both s.t. their respective parts of (1) and (2**). We now obtain a new quota price in the first period;

$$\tau_1 = \frac{\partial f_{F1}(q_{F1}(z_1))}{\partial q_{F1}} + \frac{g(z_1)}{z_1}\delta\tau_2 \Rightarrow$$

(5**) $$\frac{\partial f_{F1}}{\partial q_{F1}} = \tau_1 - \frac{g(z_1)}{z_1}\delta\tau_2,$$

since only $g(z_1)$ is transferred to the second period (note that multiplying (5**) by z_1 and rearranging gives the total value of the quota z_1). Hence $\tau_1 = \tau_1(z_1, \tau_2)$. The use of history dependence also gives a new quota price in the second period;

(6**) $\tau_2 = \dfrac{\partial f_{F2}(q_{F2}(g(z_1)+z_2))}{\partial q_{F2}}$

Thereby making (again abusing notation)

$\tau_2 = \tau_2(g(z_1)+z_2)$, making $z_2 = z_2(g(z_1))$.

Using the same procedure as for the durable model at the beginning of this note, results in the following equivalent new equations;

(7**) $\dfrac{\partial f_{M2}}{\partial q_{M2}} = \tau_2(g(z_1)+z_2) + \dfrac{\partial \tau_2}{\partial z_2} z_2$

(8**) $\dfrac{\partial f_{M1}}{\partial q_{M1}} = \tau_1(z_1) + \dfrac{\partial \tau_1}{\partial z_1} z_1 - \delta \dfrac{\partial g}{\partial z_1} \tau_2$,

Comparing (5**) and (8**) reveals that contrary to the case of the durable model, efficiency within the first period may be satisfied for a given g function. The intuition behind this is that when the fringe is *given* historic rights depending on how much was bought from the monopolist, the monopoly power is reduced (or eradicated when the optimal amount is given to the fringe).

Hence equating (5**) and (8**) gives the following function

$$g'(z_1) - \frac{1}{z_1} g(z_1) = \frac{\partial \tau_1}{\partial z_1} \frac{z_1}{\delta \tau_2}$$

However, this is a simplification, since equation (6**) says τ_2 is also a function of z_1, making the solution of the actual differential equation non-trivial. Hence in order to find a g function we assume that τ_2 is independent of z_1. We solve this non-homogeneous first order linear differential equation for g, obtaining

$$(9)\quad g(z_1) = z_1\left(\frac{\tau_1}{\delta\tau_2} + K\right),$$

where K is a constant of integration (see Appendix for calculation). Hence given the assumptions made and a history dependence function g as described in (9), efficiency within the first time period is secured.

Similarly, securing efficiency within the second period requires the equalisation of (6**) and (7**), which does not hold as we see that the fringe has higher marginal productivity of quota than the monopolist within the second time period, unless $\frac{\partial \tau_2}{\partial z_2} z_2 = 0$.

When equating (8**) and the discounted value of (7**), that is securing efficiency *between* time periods for the monopolist, we observe these two equations will only be equal if

$$(10)\quad \frac{\partial g}{\partial z_1} = \frac{1}{\delta\tau_2}\left(\tau_1 + \frac{\partial \tau_1}{\partial z_1} z_1 - \delta\left(\tau_2 + \frac{\partial \tau_2}{\partial z_2} z_2\right)\right).$$

Comparing (5**) and (6**) gives us the requirements for efficiency over time for the fringe, namely that:

$$(11)\quad g(z_1) = (\tau_1 - \delta\tau_2)\frac{z_1}{\delta\tau_2} = z_1\left(\frac{\tau_1}{\delta\tau_2} - 1\right)$$

Hence we see that the g function for time efficiency is the same for both the monopolist and the fringe, since the derivative of (11) gives (10). We see from (11) that for $\tau_1 > \delta\tau_2$, $g>0$ and vice versa. That is, if $\delta\tau_2 > \tau_1$, the monopolist has an incentive to hold back the sales of quota in order to sell more in the second period for a higher price. The optimal g remedies this by reducing the allocation to the monopolist in this situation.

From equations (9) and (11) we see that it is possible to ensure at least market efficiency (in the first time period) *or* overall time efficiency in the history dependent model, hence this model has the potential to outperform the durable model, which can ensure neither efficiency type. The history dependent model can, by choosing a g as defined in (9) match the leasing model's time efficiency as shown above under the described conditions. The history dependent model has the potential to more generally ensure time efficiency than the leasing model does. By equating equations (9) and (11) we find the condition under which both market (in the first time period) and time efficiency is secured in the history dependent model is given by K=-1. Hence, for this value of K, and the conditions assumed, the history dependent quota allocation model opens for market and time efficiency, and the trade-off between the two is avoided.

Conclusion

In this paper we study market and time inefficiency in a natural resource rights based institution, in order to shed light upon relevant and central issues regarding the optimal way of allocating rights. The time and irreversibility issue of rights allocation has long been discussed in the fisheries (Mathiasson, 1992), yet in most cases long term allocations seem to be the rule. Market inefficiency in the shape of market power has been increasingly debated in the aftermath of the introduction of individual transferable quotas (ITQs) in fisheries. Quota concentration was also prior to ITQ implementation seriously considered by policymakers (Gauvin, Ward and Burgess, 1994; Hersoug, 2002). Despite measures taken to avoid concentration, quota is found to be on fewer and fewer hands (see overview in Armstrong and

Sumaila, 2001). In this paper three different dynamic mechanisms of allocating rights in the presence of market power are presented, the first being the durable quota model, where rights are allocated for both time periods studied. In this case we observe both market and time inefficiencies. This model approximates most of the ITQ systems in place today. The second model presented is a so-called leasing model, where rights are only allocated short term. In this scenario there is greater potential for ensuring time efficiency, as agents can appropriate the optimal amount of quota in each time period. Finally, a history dependent quota allocation model is presented, where quota allocations in the second period are made conditional upon quota bought or sold in the first period. An optimal history dependent allocation can eliminate either market power or time inefficiencies, and under specific conditions both. The system works in such a way, that if a quota monopolist has an incentive to cash in on a higher price in the second period, its allocation will be reduced in order to reduce the monopsony power. The allocational mechanism is simple to operate, as it only depends on the prices in the two periods and what is bought or sold in the first time period.

A remaining question is; on the applied side, are there any *actual* history dependent allocations that are modelled in this fashion? When studying actual ITQ systems in operation today, we find several different mechanisms in play. A comprehensive ITQ management system was introduced for the first time worldwide in New Zealand in the 1980s. The initial allocation of fish was made in tons based on historic harvests. The allocation was highly transferable, only limited by some maximum clauses regarding concentration of quota. As the fisheries managers later found that aggregate harvest was too high for the existing stocks, a buy-back scheme was introduced. This scheme was not sufficient, and proportional cuts were also required before the regime became one of transferable harvest shares (Hersoug, 2002). Australia implemented a similar system for some fisheries (Hannesson, 1991). Iceland's ITQ system is a harvest share regime, in the sense that the ITQs are a fixed share in all perpetuity, as described by the durable model in this paper. Initial allocations were mainly dependent upon historic harvest (Arnason, 1993). We see that all the above ITQ systems most closely resemble the durable model presented here, and hence do not secure market or time efficiency in the presence of market power. In Namibia, where there is not a traditional ITQ system in place, we do however observe a management system in some ways similar to the history dependent model. Here quotas are allocated for a set price to different firms. The quota allocation time period is amongst other things dependent upon the firms' degree of Namibian ownership or employment (Oelofsen, 1999). The firms cannot decline the allocated quota or ministerial price demanded (unless they decide to not fish the species in question at all in Namibian waters), but can lease quota to other users. However, if quota is leased out over a long time period, this will influence the amount of quota the firms are offered the next time around (L. Clark, pers. comm.). Hence we observe that allocation is made conditional upon the firm's selling behaviour. In this case market power issues may be eliminated, both by the fact that quotas are not allocated in perpetuity, but also by the fact that leasing of quota to other firms affects future allocations. The quota allocation mechanism in Estonia (Vetemaa et.al., 2002) also has similarities with the history dependence model presented here. In Estonia 90% of the total allowable harvest is allocated according to historic catch. The remaining 10% is auctioned. The allocated quota can be transferred. Hence in the next allocation round the acquired or sold quota in the previous period will affect the allotted quota to the agents in the fishery. However, it remains to be studied whether these history dependent allocations mechanisms are able to reduce the potential market power inefficiencies in the quota market. This due to the fact that the results from this study show that not just any old history dependent mechanism will do the job, but a specific history dependent design for the fishery in question is demanded in order for efficiency to be secured.

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Appendix

In the following we calculate g for efficiency within the first time period. Equating (5**) and (8**) gives the following function

$$g'(z_1) - \frac{1}{z_1} g(z_1) = \frac{\partial \tau_1}{\partial z_1} \frac{z_1}{\delta \tau_2}$$

Dividing through by z_1 gives

$$\frac{g'}{z_1} - \frac{1}{z_1^2} g = \frac{\partial \tau_1}{\partial z_1} \frac{1}{\delta \tau_2}$$

Since $\frac{g'}{z_1} - \frac{1}{z_1^2} g = \frac{d}{dz_1} \frac{g}{z_1}$, the above becomes

$$\frac{g}{z_1} = \int \frac{\partial \tau_1}{\partial z_1} \frac{1}{\delta \tau_2} dz_1 \text{ ,}$$

In order to simplify we assume τ_2 is independent of z_1, resulting in

$g(z_1) = z_1 (\frac{\tau_1}{\delta \tau_2} + K)$, where K equals the constant of integration.